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Heat Flow at the Spreading Centers of the Guaymas Basin, Gulf of California

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Fifty-four new heat flow measurements in the central troughs of the Guaymas basin support the hypothesis that they are sites of active intrusion. In the northern trough a distinct pattern of hydrothermal cooling is revealed, with venting along the western boundary fault of the trough. In the southern trough an analogous pattern is apparently superimposed upon a conductive cooling anomaly associated with a recent central intrusion. The discharge of thermal waters occurs along the boundary faults and through other faults associated with a possible horst block located in the north central floor of the southern trough. The heat flow patterns suggest that the intrusions are episodic and do not occur simultaneously along the length (15–40 km) of a spreading segment. A review of all available heat flow measurements for the Guaymas basin suggests that most of the recharge for a pervasive regional hydrothermal system is limited to the central depressions, with perhaps some contribution from pore water. The discharge of thermal waters occurs predominantly in the central depressions and possibly along the boundary transform faults and fracture zones. The regions of the basin more than a few kilometers in distance from the spreading axis, although presumably underlain by a hydrothermal system, are probably not the location of numerous vents or recharge zones.

INTRODUCTION

The Gulf of California encompasses a diverging section of the complicated boundary between the Pacific and North American plates (Figure 1). Owing to its position within a complex evolution of such plates [e.g., *Atwater,* 1970] the gulf is considered a transition region between normal sea floor spreading on the East Pacific Rise to the south and transform motion along the San Andreas fault system to the north. A rifting geometry oblique to a small circle about the North American–Pacific pole of rotation requires that sea floor extension in the central Gulf of California take an unusual form: long transform faults dominate short sea floor spreading segments [*Moore,* 1973; *Bischoff and Henyey,* 1974; *Sharman,* 1976]. Extremely high sedimentation rates, both terrigenous and biogenic [*van Andel,* 1964; *Calvert,* 1966], combine with the oblique rifting geometry to prevent the development of many characteristics normally attributed to sea-floor-spreading systems. Thus elevated topography, rugged volcanic terrain, and identifiable magnetic anomalies are absent at the spreading centers of the central Gulf of California [*Larson,* 1972; *Moore,* 1973]. Sea floor spreading segments in this region are identifiable as a set of topographic basins connected by prominent transform faults [*Moore,* 1973]. These have developed in a regular pattern [*Sharman,* 1976] consistent with models and analogs of spreading plate boundaries [*Oldenburg and Brune,* 1972]. Within the basins, active spreading is marked by linear central depressions perpendicular to the transform faults. In the absence of identifiable magnetic anomalies, this interpretation is supported by heat flow measurements. Of the 152 measurements of conductive heat flow in the Guaymas basin, all but 2 of the 54 values above 6 HFU (1 HFU = 1×10^{-6} cal/cm^2 s) are located within 7 km of the central depression or transform faults. Similarly, all but 1 of the 24 heat flow values below 2.5 HFU are located in or immediately adjacent to these central depressions. *Lawver et al.* [1975] and *Lawver and Williams* [1979] suggested that these extremes in conductive heat flow were due to recent intrusions and related hydrothermal systems.

In preparation for drilling at several locations in the Guaymas basin by the Deep Sea Drilling Project (DSDP, *Glomar Challenger*) in the winter of 1978–1979, a site survey was conducted in the Guaymas basin in February and March 1978 aboard R/V *Thomas Washington* of the Scripps Institution of Oceanography. Undertaken with joint Mexican-American participation, the site survey work included multichannel and single-channel seismic profiling, gravity, magnetics, coring, water sampling, and heat flow measurements. The heat flow surveys were located at possible geothermal drill sites at the spreading centers of the Guaymas basin to determine the thermal regimes at those sites.

THE GUAYMAS BASIN

The Guaymas basin is reasonably well outlined by the 1500-m depth contour in Figure 2. Approximately 240 km long by 60 km wide, it contains a distinct central depression just over 2000 m deep, divided into two troughs that are offset consistent with right lateral North America–Pacific plate motion. The North America–Pacific pole of rotation in northeast Canada at 48.8°N, 73.9°W [*Minster and Jordan,* 1978] implies that the Guaymas basin spreading rate does not differ significantly from that measured on the East Pacific Rise at the mouth of the Gulf of California, 3.1-cm/yr half rate [*Larson,* 1972]. Therefore despite the lack of magnetic anomalies in the Guaymas basin, we can assume the spreading half rate there should be about 3 cm/yr. Extremely rapid sedimentation of 1–4 m/1000 yr blankets the entire basin with diatomites and hemipelagic silty clays [*van Andel,* 1964; *Calvert,* 1966]. The clays increase in grain size toward the northeast, presumably indicating a source, for example, the Yaqui River, in that direction. Terrigenous material composes 50–70% of the sediment. The remainder is biogenic, principally siliceous but with some coccoliths.

The central depressions average 3–4 km wide and 50–150 m deeper than the surrounding sea floor. A transform fault with no bathymetric expression is assumed to offset the 40-km-long northern trough about 20 km from the 15-km-long southern

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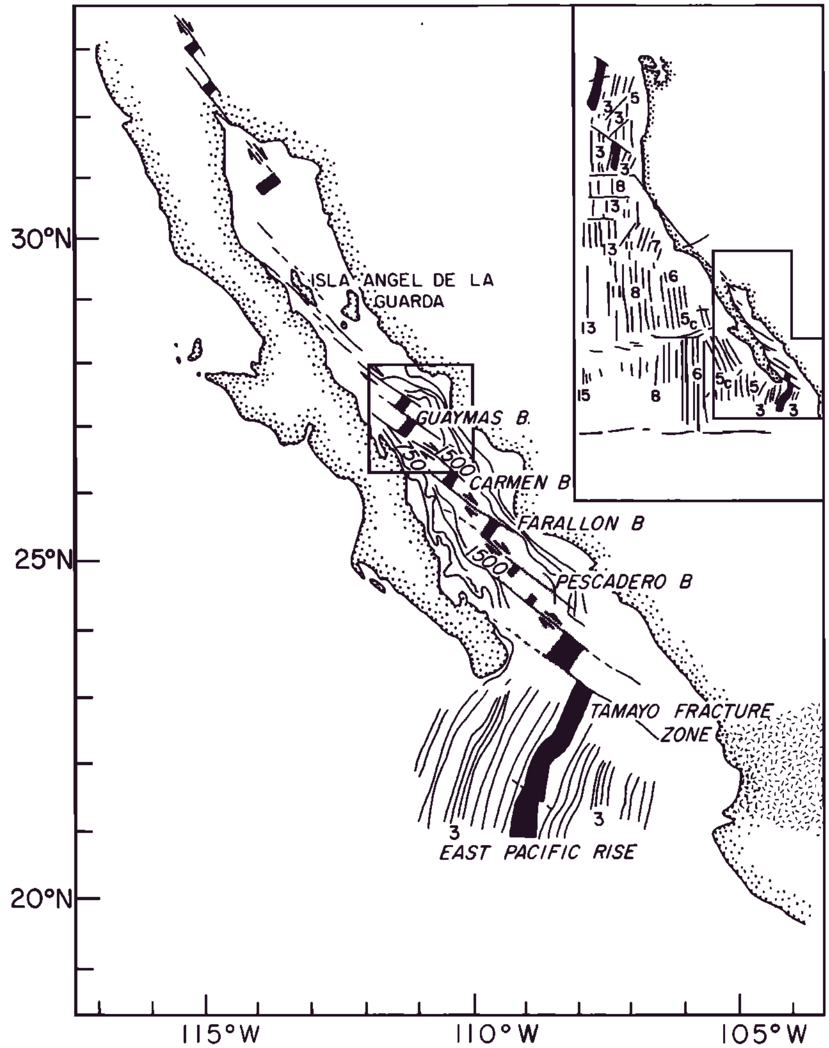

Fig. 1. Bathymetric contours and generalized tectonics of the Gulf of California. Contours in uncorrected meters. The heavy black lines represent possible spreading centers, the continuous and dashed lines at right angles to these are fracture zones, and the fine stippled areas are the enclosed basins [after *Larson,* 1972; *Lomnitz et al.,* 1970, Figure 3]. The inset in the upper right-hand corner, which shows the distinctive magnetic lineations and anomaly numbers in the northeastern Pacific, has been taken from *Atwater* [1970]. The rectangular area outlined in the center shows the region covered by Figure 2.

trough (Figure 2). As large-scale extensional features the depressions are apparently underlain by intrusive masses of uncertain geometry, as suggested by reflection profiles of the southern trough [*Lawver et al.,* 1975]. The intrusions are

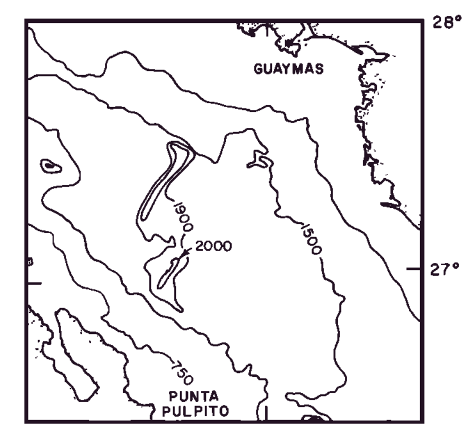

Fig. 2. Bathymetric contours of the Guaymas basin in uncorrected meters. See Figure 1 for area covered by this map.

coupled with some extension and thinning of the overlying lithified sediments; consequent normal faulting produces steep-walled central troughs [*Lonsdale,* 1978], reminiscent of the grabens of the Basin and Range province [*Thompson,* 1966; *Stewart,* 1971].

One or more 5- to 20-m-thick layers of flat lying, acoustically transparent sediment cover the central depression to depths of about 50–100 m (Figure 3). The total sediment thickness is poorly determined but probably averages about $\frac{1}{2}$ km. In each trough the recent undisturbed sediment cover is thickest near the edges of the Guaymas basin and thins toward the presumed central transform fault, suggesting a significant land- or shelf-derived sediment component. Short gravity cores (1–2 m) throughout the Guaymas basin sampled uniform green hemipelagic diatomaceous silty clays.

The various neotectonic features, visible on the 3.5-kHz records along the central depressions (for example, the horst at 2220 UT in Figure 3*a*, where *Z* is universal time UT), are best explained by extensional processes in the thick, semilithified sedimentary section. Direct observations from DSRV *Seacliff* [*Lonsdale,* 1978] indicate that the large peaks, slightly elongate parallel to the depressions and of heights no greater than

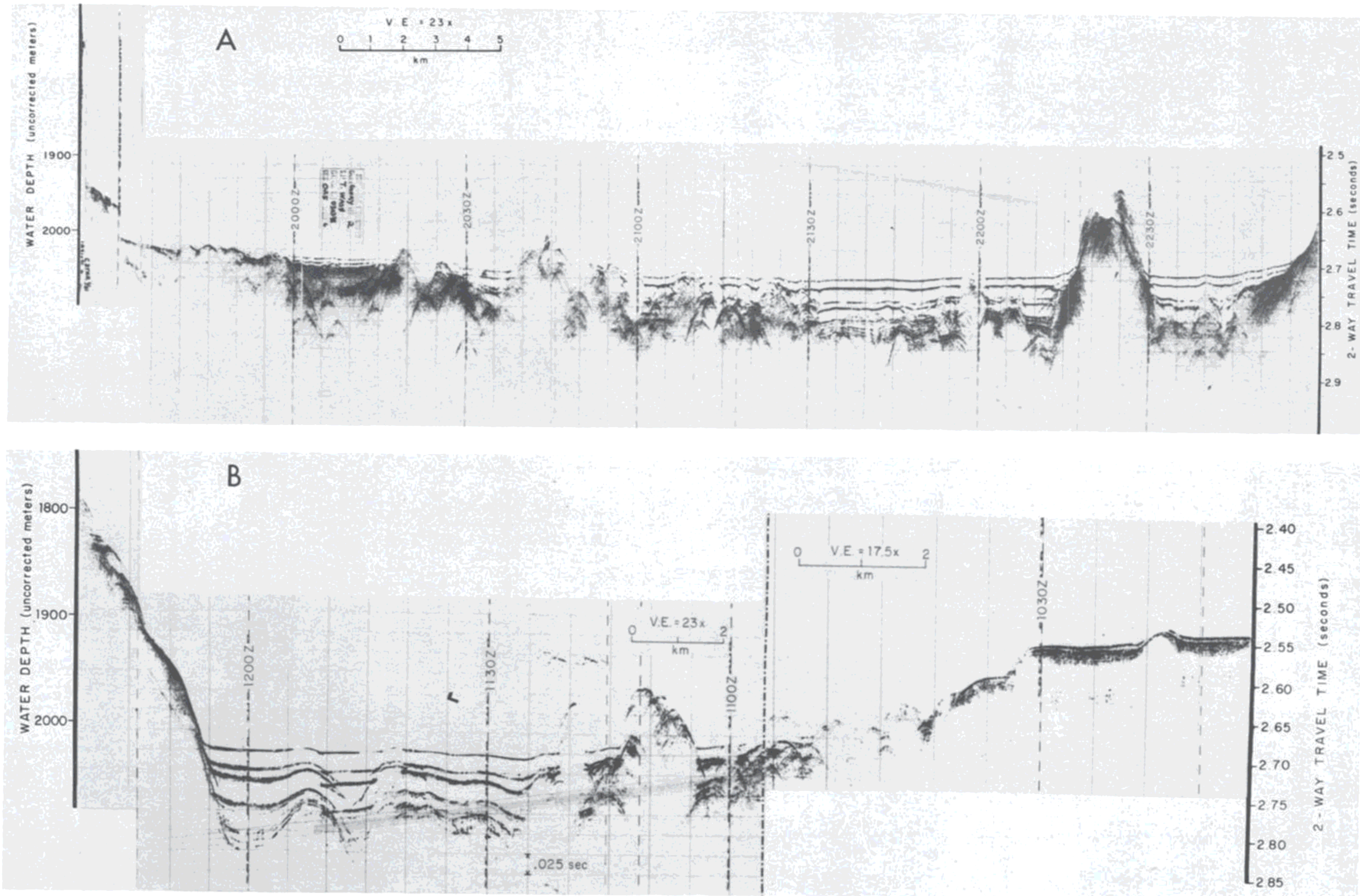

Fig. 3. Photographs of records from the R/V *Thomas Washington*'s 3.5-kHz seismic profiler: (*a*) northern trough and (*b*) southern trough. Both profiles run down the long axis of the trough with south on the left and north to the right. Locations of tracks and times are shown on Figures 4*a* and 4*b*. Note the disturbed sediment between 2100 and 2120 UT (*Z* is universal time, UT) in the northern trough and between 1040 and 1055 UT in the southern trough.

TABLE 1. Heat Flow Data From the Guaymas Basin From Cruise GUAY 3 of the R/V *Thomas Washington*

Station	Position	Water Depth, m	*P*	*N*	*Q*	Remarks
1.1	27°18.3′N, 111°30.5′W	2010	3.5	4	5.3	
1.2	27°18.4′N, 111°30.7′W	2000	3.5	2	22.7	lower two thermistors were over range, >5°C above bottom water temperature
1.3	27°18.6′N, 111°31.0′W	2000	3.5	2	31.2	
1.4	27°18.7′N, 111°31.3′W	1880	3.5	4	5.2	
3.1	27°15.7′N, 111°30.2′W	2000	3.5	3	2.4	
3.2	27°15.8′N, 111°30.4′W	2000	3.5	3	1.9	
3.3	27°15.9′N, 111°30.6′W	2010	3.5	3	2.1	
3.4	27°16.0′N, 111°30.8′W	2010	3.5	3	0.6	
3.5	27°16.2′N, 111°31.2′W	2000	3.5	3	2.1	
3.6	27°16.3′N, 111°31.3′W	2000	3.5	3	6.7	
4.1	27°02.0′N, 111°22.5′W	1940	3.5	3	5.5	
6.1	27°00.8′N, 111°24.5′W	1990	3.5	4	16.6	
6.2	27°00.5′N, 111°24.8′W	2020	3.5	4	13.9	
6.3	27°00.0′N, 111°25.3′W	2020	3.5	4	5.1	
6.4	26°59.5′N, 111°25.6′W	2020	3.5	4	3.1	
6.5	26°59.4′N, 111°25.6′W	2010	3.5	4	2.4	
7.1	27°01.8′N, 111°23.2′W	2000	3.5	4	6.3	
7.2	27°01.9′N, 111°23.3′W	2010	3.5	4	6.2	
7.3	27°01.9′N, 111°23.4′W	2000	3.5	4	6.3	
7.4	27°02.1′N, 111°23.6′W	2010	3.5	4	11.1	
7.5	27°02.3′N, 111°23.9′W	2010	3.5	4	7.5	
7.6	27°02.5′N, 111°24.1′W	2010	3.5	4	4.4	
7.7	27°02.7′N, 111°24.3′W	2010	3.5	4	3.9	
8.1	27°02.9′N, 111°24.2′W	2000	3.5	4	5.5	nonlinear gradient
8.2	27°03.2′N, 111°24.2′W	1970	3.5	4	5.0	
8.3	27°03.3′N, 111°24.3′W	1970	3.5	4	3.8	
8.4	27°03.5′N, 111°24.5′W	1970	3.5	4	2.6	
8.5	27°03.6′N, 111°24.7′W	1960	2.5	3	2.0	partial penetration
9.1	26°58.4′N, 111°25.6′W	2020	3.5	4	2.6	
9.2	26°58.5′N, 111°25.8′W	2020	3.5	4	2.9	
9.3	26°58.6′N, 111°26.0′W	2020	3.5	4	2.4	
10.1	26°58.7′N, 111°24.4′W	1970	2.5	3	3.2	partial penetration
10.2	26°58.8′N, 111°24.8′W	2000	2.5	3	3.2	partial penetration
10.3	26°59.0′N, 111°25.2′W	2020	2.5	3	3.5	partial penetration
10.4	26°59.1′N, 111°25.4′W	2020	3.5	4	3.5	
10.5	26°59.2′N, 111°25.6′W	2020	2.5	3	4.9	partial penetration
11.1	26°59.8′N, 111°25.3′W	2020	3.5	4	9.9	
11.2	26°59.7′N, 111°25.1′W	2020	3.5	4	10.6	
11.3	26°59.6′N, 111°24.9′W	2020	3.5	4	10.4	
11.4	26°59.4′N, 111°24.8′W	2020	3.5	4	10.8	
11.5	26°59.2′N, 111°24.7′W	2000	3.5	4	7.4	
11.6	26°58.9′N, 111°24.7′W	1990	3.5	4	4.4	
12.1	27°20.9′N, 111°28.5′W	2030	3.5	4	12.1	
12.2	27°20.9′N, 111°28.6′W	2030	3.5	4	9.6	
12.3	27°20.9′N, 111°28.7′W	2000	3.5	4	7.9	
12.4	27°20.9′N, 111°28.9′W	1970	3.5	4	11.5	
12.5	27°20.9′N, 111°29.1′W	1950	3.5	4	17.1	nonlinear gradient
13.1	27°18.0′N, 111°28.7′W	1960	3.5	4	3.1	
13.2	27°18.2′N, 111°29.1′W	1980	3.5	4	3.6	
13.3	27°18.2′N, 111°29.4′W	2000	3,5	4	2.4	
13.4	27°18.3′N, 111°29.8′W	2010	3.5	4	12.0	
13.5	27°18.4′N, 111°30.0′W	2010	3.5	4	5.3	
13.6	27°18.5′N, 111°30.1′W	2010	3.5	4	2.7	
13.7	27°18.5′N, 111°30.2′W	2010	3.5	4	4.8	

Water depths are in uncorrected meters. *P* is the estimated sediment penetration of the lowermost thermistor used for temperature gradient determinations. *N* is the number of thermistors used for sediment temperature gradient measurements. *Q* is heat flow in heat flow units (10^{-6} cal cm^{-2} s^{-1}).

the depth of the depressions, are probably sedimentary horst blocks and not volcanic in origin. The common hummocky terrain, especially visible in the middle of the northern trough (Figure 3), may result from very recent extension across the trough, producing an orthogonal pattern of small normal faults.

Our heat flow surveys centered on two possible geothermal drill sites, one in each trough of the Guaymas basin. In the southern trough we returned to the geothermal anomaly reported by *Lawver et al.* [1975], which was attributed primarily to intrusive and conductive processes. In the northern trough we surveyed the region in which hydrothermal deposits were observed and sampled and where active or very recently inactive hydrothermal vents were seen from the *Seacliff* near the steep western boundary fault [*Lonsdale*, 1978]. In addition to an accurate description of the thermal state of these sites our goals included the determination of the causes of the observed local heat flow anomalies and the resolution of the regional conductive and convective heat fluxes.

MEASUREMENTS AND TECHNIQUES

Fifty-four new heat flow measurements are reported in Table 1. They were measured using the Woods Hole Oceanographic Institution's multipenetration heat flow probe [*Von Herzen and Anderson,* 1972]. The version used in our measurements consisted of a $3\frac{1}{2}$-m probe fitted with four outrigger thermistors at 1-m intervals. Because of problems with equipment early in the cruise the acoustic telemetry capability of this instrument was unavailable to us.

Navigation of the ship was accomplished by a combination of radar fixes taken at each station, satellite fixes, sophisticated dead reckoning, and bottom navigation using the bathymetric charts in Figure 4. The position of the instrument at each heat flow penetration was determined in relation to the ship by using an empirical relationship developed on previous cruises when acoustic navigation was available. The principal variable is the wire angle, both vertical and azimuthal. Station locations are accurate to within 1 km, but the relative position of individual penetrations on a single station is probably better than 300 m. Our positioning in the direction normal to the axis of the depressions is superior to that parallel to the axis of the depression because bathymetric charts are useful as a navigational aid only in the direction in which the depth varies.

Thermal conductivities were measured on cores by the needle probe method [*Von Herzen and Maxwell,* 1959]. The new values compared quite closely with those reported by *Lawver and Williams* [1979]. On the basis of these results we use an assumed value of 1.7×10^{-3} cal/cm s °C for all of our measurements. The errors that could result from variations in conductivity are small in comparison to the variations in the measured thermal gradients.

The heat flow values listed in Table 1 are the product of thermal conductivity and measured thermal gradients corrected for tilt. The heat flow instruments have two tilt indicators, one indicating >30° tilt and the other >15° tilt. Where the instrument tilted <15°, no correction is made. For tilts between 15° and 30° the correction we assume increases the observed gradient 8% (1 − cos 23.5°). For tilts >30° a 14% (1 − cos 30°) correction is applied if the observed gradient indicates a full penetration. If full penetration is not indicated, the measurement is either discarded in the case of low gradients or tabulated as a minimum value in the case of high observed gradients.

DISCUSSION

Lawver and Williams [1979] used the measurements available to them at the time to attempt to deduce the geothermal budget of the central gulf. They tried to account for four major mechanisms of crustal heat transfer: thermal conduction through the sea floor, heat loss to the adjacent cold continental blocks, the heating of sediments and adjustment of crustal temperatures resulting from the rapid accumulation of sediments, and the discharge of thermal waters. Their measurements showed that outside the central depressions and transform faults the Guaymas basin has uniform regional conductive heat flow of 4.3 ± 1.1 HFU. They concluded, on the basis of the discrepancy between measured heat flow (corrected for sedimentation and lateral heat flow) and theoretical cooling plate heat flow predictions, that hydrothermal heat loss must be a significant process even through the thick sediments of the central gulf.

The so-called 'heat flow anomaly,' observed at nearly every surveyed spreading center and used to infer the hydothermal heat loss, is generally difficult to measure because the thin sediment cover over the rough topography of very young crust precludes genuinely representative heat flow measurements. In the central gulf, however, the thick sediment blanket allows accurate determination of the conductive heat loss for all crustal ages. However, two processes greatly complicate the determination of the heat flow anomaly in the Guaymas basin. First, the high sedimentation rate leads to an intrusive mode of crustal accretion with poorly developed magnetic anomalies [*Larson,* 1972; *Moore,* 1973; *Klitgord et al.,* 1974], so that crustal ages cannot be determined remotely. Second, since the spreading system is young and probably not yet fully developed, the thermal processes have probably not yet reached a stationary state, so the predictions of heat flow for a cooling plate may not be applicable. Some combination of strike slip faulting, crustal extension, and sea floor spreading has presumably occurred in the Guaymas basin for the last 4 m.y. that the East Pacific Rise has been actively spreading at the mouth of the Gulf [*Larson,* 1972]. Oceanic crust is indicated by a reversed seismic refraction station NW-SE across the Guaymas basin [*Phillips,* 1964]. Petrologic studies [*Batiza,* 1978] have shown that Isla Tortuga, lying on the strike of the presumed central Guaymas basin transform fault and composed of fairly typical midocean ridge tholeiitic basalt, erupted within the last million years.

The expected increase of depth with age due to cooling and contraction of oceanic crust is not observed in the Guaymas basin; instead, depths decrease away from the central troughs. Most of this discrepancy is probably due to the effects of a high sedimentation rate. Sediments are less dense than the basement rocks, and if they accumulate fast enough, they can cause a decrease in depth with age even though the basement continues to subside. If we corrected for these density differences, the apparent age versus depth discrepancy might vanish. However, we do not have adequate data to make this correction.

We contend that the average heat flow of 6.2 HFU in the central depressions represents a significant heat flow anomaly. In order to evaluate this anomaly it is necessary to have an estimate of the anomaly predicted by various accretion models. We consider the thermal predictions of a cooling plate model where we require an integrable heat flow at the origin of spreading, and thus the results of *Sleep and Wolery* [1978] seem to apply. The geology requires that we average the predicted heat flow over some distance, ranging from the approximate graben width, 3 km, to the 40-km-wide zone outside of which *Lawver and Williams* [1979] found a uniform average heat flow. The 40-km width will adequately account for jumps in the location of the spreading center discussed by *Sharman* [1976]. At an assumed full spreading rate of 6 cm/yr this is equivalent to averaging over 0.05–0.67 m.y. Owing to the uncertainties in the spatial and temporal nature of accretion this is a very difficult age range in which to make estimates with any confidence. As a result we will only make a few simple observations. *Sleep and Wolery* [1978] did not publish their model, but they did give an average heat flow between 0 and 1 m.y. of 23 HFU. The predicted average for a shorter time pe-

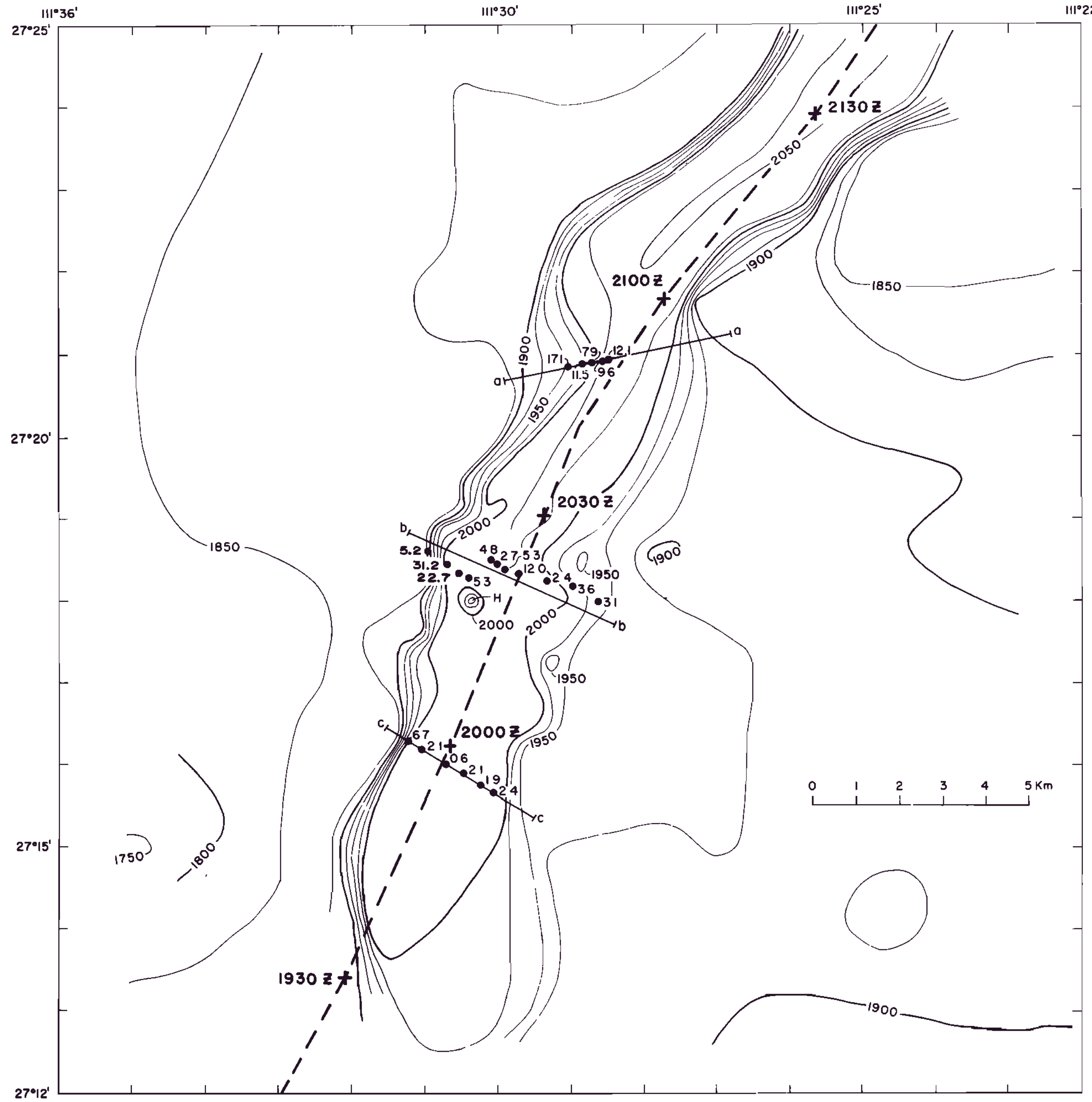

Fig. 4*a*

Fig. 4. Heat flow and bathymetry from the central trough of the Guaymas basin. Heat flow values are in heat flow units. Only heat flow values from R/V *Thomas Washington* GUAY leg 3 and *Lawver et al.* [1975] are shown. Profiles a-a' through f-f' refer to Figure 5. (*a*) Southern end of the northern trough with bathymetry in uncorrected meters at a 20-m contour interval. (*b*) Southern trough with bathymetry in uncorrected meters at a 25-m contour interval. Dashed lines and times refer to ship tracks for the seismic reflection profiles of Figures 3*a* and 3*b*. (*c*) Northern end of the northern trough with bathymetry in uncorrected meters at a variable contour interval (figure taken from *Lawver and Williams* [1979]).

riod would be higher. From these estimates we can see that the predicted heat flow is at least 3 times our observed average, thus making the discrepancy between observed and predicted heat flow unquestionable. We assume that the bulk of this discrepancy can be explained by our inability to measure the hydrothermal component of heat loss.

In the discussion that follows we first consider the near-surface thermal states at several locations. We choose, on the basis of an initial, subjective assessment, to divide the 101 central trough heat flow measurements into three geographically localized groups. The first group comprises the 42 measurements in the southern trough. These display a two-dimensional variation of heat flow over 40–50 km^2 with values ranging from 2 to greater than 30 HFU (Figures 4*b*, 5*d*–5*f*, and 6*a*). The second group includes 22 new values in the southern end of the northern depression, which also has a large range of values, less than 1 to greater than 31 HFU and a similar distribution of values. However, this group shows large spatial variations over much shorter distances than the first group, suggesting an active hydrothermal system (Figures 4*a*, 5*a*–5*c*, and 6*b*). The third group consists of 33 measurements [*Lawver and Williams,* 1979] in the northern end of the northern trough, which exhibits a much tighter range of values, 1.8–7.7 HFU, and a lower mean (Figure 6*c*). We also consider a group of 15 measurements from transform faults reported by *Lawver and Williams* [1979]. We then conclude with a dis-

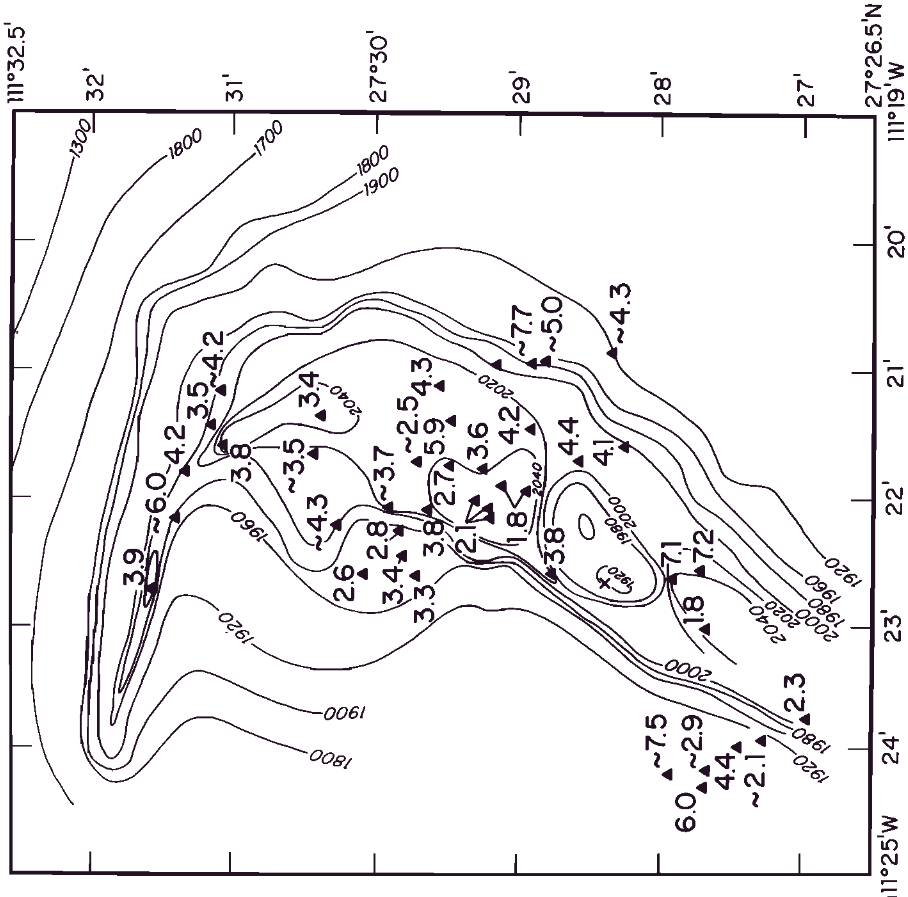

Fig. 4c

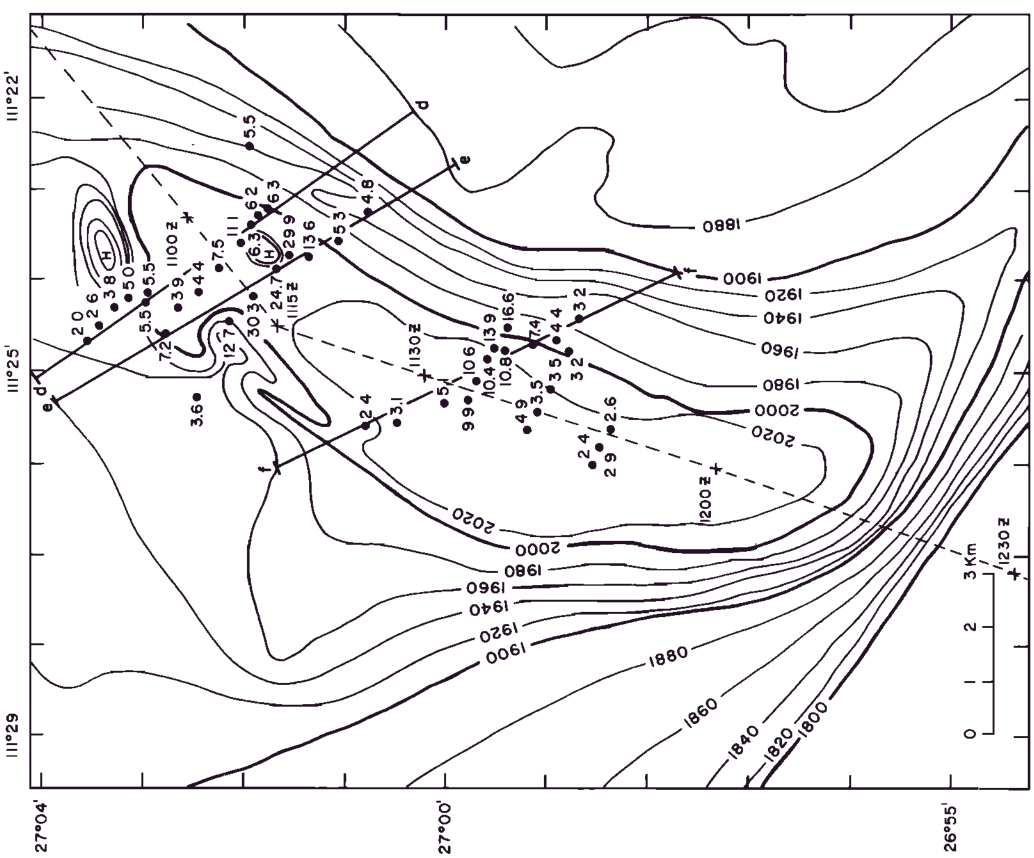

Fig. 4b

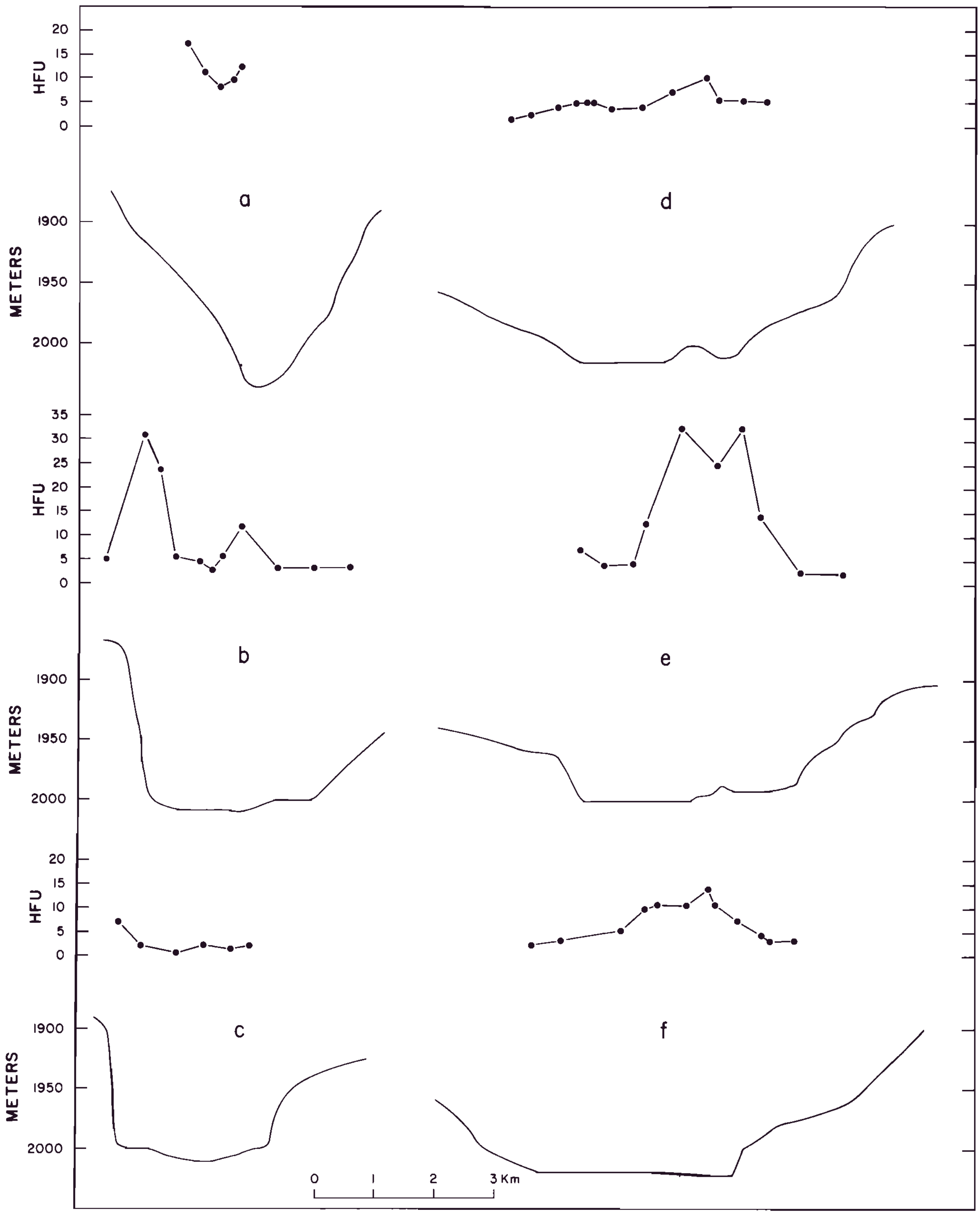

Fig. 5. Profiles of heat flow and simplified bathymetry taken from Figure 4. Only heat flow values within 0.5 km of the profile line are shown. Vertical exaggeration in the bathymetry is approximately 11:1.

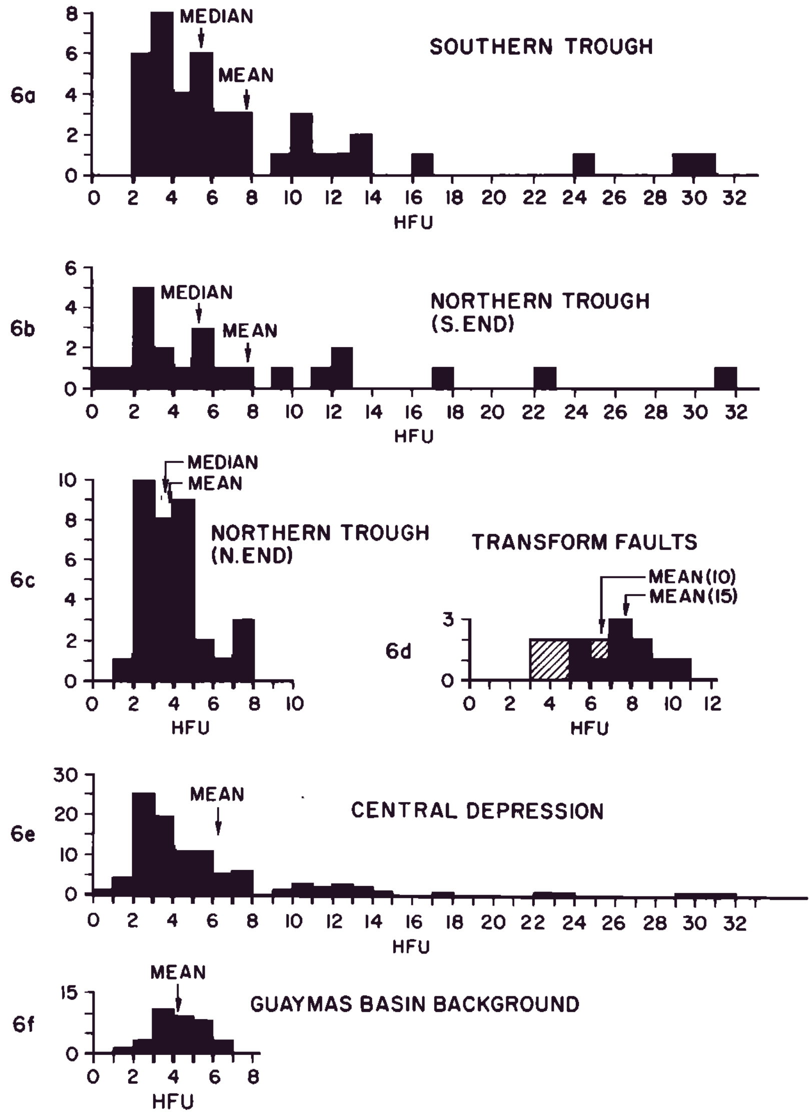

Fig. 6. Histograms of heat flow. The 42 values in Figure 6*a*, 22 values in Figure 6*b*, 33 values in Figure 6*c*, and 101 values in Figure 6*e* are taken from in or within 3 km of the central depressions. The 36 values in Figure 6*d* come from areas in the Guaymas basin that are over 3 km from the central depressions and are not adjacent to transform faults or fracture zones. The 15 values in Figure 6*d* are from areas in or adjacent to transform faults or fracture zones. The hatched area illustrates how the histogram would look with the five values from the northern end of the northern trough removed.

cussion of the implications of our data for the regional geothermal processes, with particular attention to a regional hydrothermal system.

The Local Surveys

The Southern Trough

The starting point for our survey, the geothermal anomaly of *Lawver et al.* [1975] (Figure 5*e*), shows a fairly well defined central high with a maximum over 30 HFU, centered in the southern trough of the Guaymas basin (Figure 4*a*). New profiles across this depression, both north (Figure 5*d*) and south (Figure 5*f*) of the anomaly, do not repeat its amplitude but do show lesser heat flow highs centered in the depression. Profiles in Figures 5*e* and 5*f*, and incomplete lines farther south, reflect an apparently regular decrease in conductive heat flow to the south along the trough. The expanded data set can readily be contoured (Figure 7); the choice of contour intervals introduces only minor variations to the symmetric pattern.

The smooth spatial trends, coupled with the extreme range of heat flow values within the relatively small area of the southern trough, suggest two possible source mechanisms for the anomaly: purely conductive cooling of a shallow intrusion or near-surface conduction through the impermeable cap rock above a hydrothermally cooling intrusion. These two mechanisms are not independent, and some combination of them is probably more reasonable. However, the purely conductive model excludes the possibility that a substantial component of heat is being lost through the discharge of thermal fluids. Owing to the thermally induced buoyancy forces in fluids we would expect a hydrothermal system to develop an upward flowing limb above the intrusion spreading laterally away from it with probably a deeper lateral flow toward the intrusion. Such an advection pattern would sharpen both the amplitude of the heat flow anomaly and the transition to the regional gradient to the sides. The descending or laterally advecting fluids adjacent to the site of intrusion might depress the local heat flow to a value below the regional heat flow.

The data suggest that both convection and conduction processes are important in the southern trough. The heat flow contours (Figure 7) show a distinctive band of low heat flow

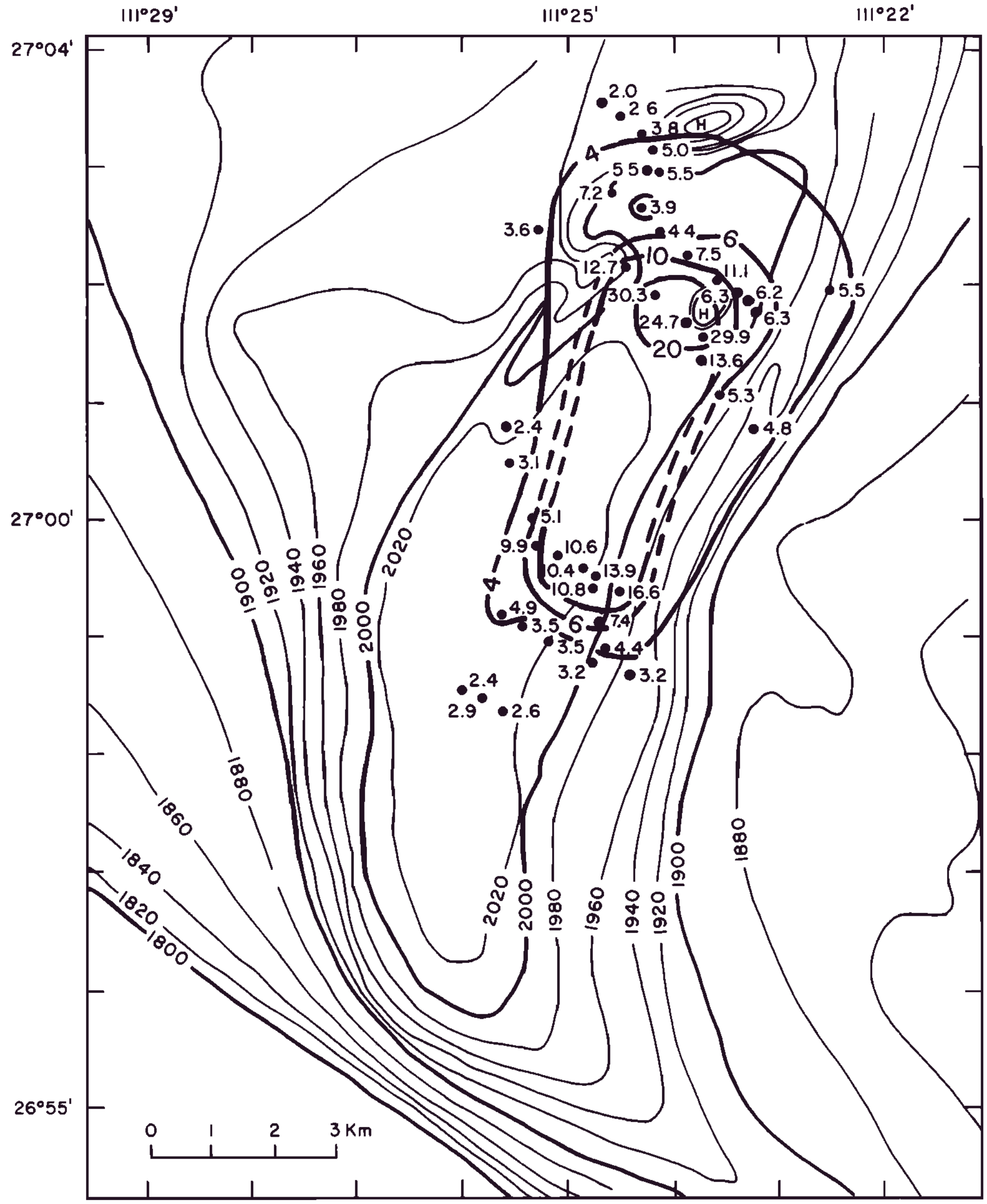

Fig. 7. Contours of heat flow in the southern trough superimposed upon the bathymetry and heat flow data from Figure 4*b*. Note that the contour interval increases from 2 HFU for the lower-heat-flow areas to 10 HFU in the high-heat-flow areas.

on the northern, western, and southern sides of the heat flow high; the data distribution is not sufficient to determine if a continuous ring of low heat flow exists around the high. Since no reasonable conductive process can result in a thermal gradient below the regional, we interpret this low heat flow to indicate descending fluids. These fluids may be seawater recharge descending into a somewhat open system or simply a downgoing limb of a convection cell in a more closed system. In the vicinity of the heat flow high the local geology allows the possibility of fault-directed discharge, especially near the three extremely high values of the profile in Figure 5*e*. In this area (Figure 4*a*) there exists a sharp local bathymetric high of shape and dimensions suggestive of similar features in the northern trough that have been directly observed to be sedimentary horst blocks, not volcanic constructions [*Lonsdale*, 1978]. If the high in the southern trough is also a horst, its boundary faults could offer the lowest-resistance path for the discharge of thermal waters above an intrusion. Such a possibility might be reflected in the sharp heat flow high measured in the immediate vicinity of the bathymetric peak.

Although the data coverage is incomplete to the north and east of the southern trough, we interpret the coupling of the central heat flow high and surrounding low to indicate a significant hydrothermal system. However, the data are also basically consistent with an important component of heat transport by conduction from a shallow intrusion, as modeled by *Lawver et al.* [1975]. The added data now give us two-dimensional control on a possible intrusive geometry. Despite the implicit difficulties in resolving the spatial properties and temporal behavior of a conductive source, and even if the heat flow pattern is disturbed by convection, the shape and symmetry of the heat flow contours (Figure 7) suggest rough bounds for the dimensions of the source. The recent intrusions apparently form a body no longer than about 5 km and no wider than about 1 km, with an older and/or deeper southern section.

The smoothness of the heat flow pattern is broken to the sides by minor heat flow highs, which are probably associated with the graben boundary faults or walls and which cannot be unequivocally interpreted. In particular, the profiles in Figures 5*d* and 5*e* show secondary highs over the western boundary fault, and the peak measurement of the profile in Figure 5*f* occurs close to the eastern slope break. These disturbances to the geothermal gradient might be explained by either of two mechanisms which the data cannot resolve: thermal topographic effects at the boundary walls or hydrothermal discharge along the boundary faults.

To estimate possible topographic effects, we approximate the geometry of the graben walls by a planar slope between two level surfaces at different elevations and assume a uniform thermal conductivity, which is probably justified here, away from intrusion sites because of the thick sedimentary cover. This idealized system has been considered by both *Jeffreys* [1938] and *Lachenbruch* [1968, 1969]; their results show that for the 2–5% boundary wall slope observed in the southern trough a 10–20% increase in heat flow should occur near the lower slope break. This figure is of the right order of magnitude to explain the peak value of the profile in Figure 5*f* but is too low to account for the heat flow increase observed at the northwestern wall. However, in this location the real geometry is much more complex than the model, so that stronger topographic effects cannot be excluded.

The similarity of idealized curves for heat conduction in this geometry and for heat flow observed near discharge vents (for example, compare *Lachenbruch* [1969] and *Sleep and Wolery* [1978] demonstrates the difficulty in distinguishing these effects, with surface gradient measurements, at any graben wall formed by active faulting. However, the topographic effect is a stationary effect, whereas hydrothermal discharge is a transient process; and heat flow variations attributed to hydrothermal discharge must first be corrected for topography. Thus we consider our observed thermal edge effects to be largely conductive effects but possibly evidence for hydrothermal venting in the southern trough.

The Northern Trough

Our data from the southern end of the northern trough of the Guaymas basin (Figure 4*a*) are indicative of hydrothermal cooling. Each of the three profiles (Figures 5*a*–5*c*) displays a heat flow high associated with the western boundary fault of roughly an order of magnitude too large an amplitude to be explained by topographic effects. The extremely high values at the boundary fault (Figure 5*b*) are probably quite near (within 1 km) the hydrothermal vent sites reported by *Lonsdale* [1978]. He also observed that the western wall near the hydrothermal sites was quite steep and relatively fresh. Therefore the western fault is presumably active enough to maintain an open conduit for the discharge of a deep hydrothermal system despite the high sedimentation rate. Indeed, this boundary fault, between the profiles in Figures 5*b* and 5*c*, is the location reported for an April 1972 shallow earthquake swarm of more than 1000 events in 6 hours [*Reichle and Reid,* 1977]. The profile in Figure 5*b* also exhibits an isolated midtrough heat flow high which is sharp enough to preclude a topographic origin as well as all but a very shallow, recent, localized intrusive origin. The proximity of this measurement to the reported hydrothermal vent sites and to observed zones of tensional faulting in midtrough sediments suggests hydrothermal discharge through the disturbed sediments, but probably being of lesser importance than at the boundary fault. Further indications for significant hydrothermal circulation in this area are provided by the consistently low midtrough values of the profile in Figure 5*c* and the low values of the line in Figure 5*b* away from presumed discharge sites. The lateral extent of these heat flow lows may indicate a widespread diffuse recharge system or deep-seated circulation of a depth and width scale comparable to the graben width (3 km). In the latter case, fluids would enter along the faults, flow laterally to the heat source, and ascend to the discharge site.

The dissimilarity of the histogram of heat flow values in the northern end of the northern trough (Figures 4*c* and 6*c*) to those of the two active geothermal sites already discussed suggests that this section of the Guaymas basin is thermally quiescent. The low mean heat flow, low standard deviation, and comparatively low ratio of standard deviation to mean are all consistent with a cooled system. The mean heat flow in this area (3.9 ± 1.6 HFU) is not significantly lower than the regional mean (4.2 ± 1.1 HFU).

The foregoing discussion leads us to suggest a qualitative model of episodic intrusive activity in the Guaymas basin similar to that reported by *Ballard and van Andel* [1977] at the Mid-Atlantic Ridge. We now have data from three distinctly different but representative stages of intrusive episodes. The southern end of the northern basin is probably the region of most recent intrusion. The sediments on the floor of the trough appear disturbed (Figure 3), and we infer that hydrothermal fluids are venting through faults. Since the high sedimentation rate tends to bury disturbed sediments rapidly, and precipitates from hydrothermal fluids quickly seal vents, very recent tectonic activity is indicated. The 1972 earthquake swarm supports this interpretation. In addition, the heat flow pattern looks somewhat immature, with extremely high and low values both present in a relatively small area. This is in contrast to the much more well developed thermal anomaly observed in the southern trough. Therefore we feel that the intrusive activity in the southern end of the northern trough is indeed very recent and may, in fact, still be occurring. In the southern trough the most recent intrusion, although still quite hot, is somewhat older, perhaps in the range of 1000–18,000 years ago, as suggested by *Lawver et al.* [1974].

In the northern end of the northern trough (Figure 4*c*) we apparently are seeing the waning stages of an intrusive episode. Here we observe a relatively confused heat flow pattern with an average value significantly lower than the more recently intruded areas.

Transorm Faults

The results so far presented suggest that hydrothermal discharge probably occurs only through breaks in the thick sedimentary cover of the Guaymas basin. Aside from the central grabens the most likely zones for faulting to occur within the sediments are along the transform faults. A histogram of 15 transform fault values [*Lawver and Williams,* 1979] is given in Figure 6*d*; the sample is small, and the interpretation necessarily ambiguous. The mean of these values, 6.6 HFU, is high and comparable to the mean in the central grabens; but the standard deviation is quite low, indicating that the dispersal of values generally observed in hydrothermal zones is not present here. Of these 15 values, 5 are also included in the northern section of the northern trough. Nine form a profile across the seismically quiet, morphologically indistinct central transform fault. These nine values range from 5.7 to 10.0 HFU. They form a heat flow high at least 4–5 km wide [*Lawver and Williams,* 1979]. The narrow range of values and apparently undisturbed sediment cover argue against a discharge origin at this particular location; the evidence suggests a deep heat source associated in some way with the transform fault. Whether this source is an upward flowing limb of a hydrothermal convection system or a recent intrusion cannot be distinguished. A magmatic origin is certainly consistent with frequent observations of intrusive activity in transform faults. Particularly relevant is the common intrusive activity seen in the Tamayo fracture zone at the mouth of the Gulf of California (K. Macdonald, unpublished data, 1979). It is possible that the recent intrusive activity on the nearest ends on both adjacent spreading segments is related to the observed thermal anomaly.

REGIONAL HEAT FLOW OF THE GUAYMAS BASIN

Figures 6*e*–6*f* present most of the heat flow data available from the Guaymas basin (except for 10 transform fault measurements). They are divided into two groups: 101 values from within and immediately adjacent to the central depressions (Figure 6*e*) and 36 values away from the central depressions and transform faults (Figure 6*f*). The previous discussion has suggested that various local processes occur within the central troughs, so the first group represents an averaging of the effects of these processes. The range of processes is reflected in the high standard deviation of the first group, 5.9 HFU, nearly as large as the mean, 6.2 HFU. Nevertheless, the higher average of this group implies a higher thermal energy state in the central depressions, supporting the earlier interpretations that they are the centers of extensional activity. The lower standard deviation of the second group implies that the near-surface thermal state outside the central depressions and transform faults is relatively constant.

Figure 3 of *Lawver and Williams* [1979] illustrates that the conductive heat flow rapidly decays to the average value (~4.3 HFU). There is no apparent decrease in conductive heat flow beyond 10–20 km from the axes of the central troughs. This cannot be explained by simple conductive cooling, sea-floor-spreading models because they require decreasing heat flow with increasing age. Numerous jumps in the location of the spreading centers could result in a more uniform distribution of heat flow. Although the evidence indicates that jumps have occurred, the location of the spreading center has never been far from the center of the basin [*Sharman,* 1976]. Rapidly accumulating sediments and lateral heat loss to cold continental blocks could conceivably contribute to this rapid decay of heat flow. *Lawver and Williams* [1979] discussed these effects but did not specify how they would influence the observed decay. The geometry and observed heat flow values argue against this being the explanation. The principle variable in the sedimentation rate is the distance to the source of the terrigenous component. These sources are north and northwest of the area. The important parameters that determine the effect of sediments on heat flow are the sedimentation rates and the total accumulation: the more rapid the sedimentation rate and greater the total accumulation, the larger the effect. Therefore the oldest parts of the new sea floor in the northwest end of the Guaymas basin should have the greatest sedimentation correction, and the youngest sea floor in the southeast end should have the smallest correction. The greatest effect of cold continental blocks will occur in the sea floor oldest and closest to the continent, and young sea floor in the center of the Guaymas basin should show the least effect. The combined effect of sedimentation and cold continental blocks should be smallest in the central basin just south of the spreading center and greatest in the north and northwest end of the basin, where we should expect the lowest heat flow. No such distribution of heat flow is apparent in the Guaymas basin [*Lawver and Williams,* 1979, Figure 4), and we assume that either these effects are not large enough to be measured or somehow the expected distribution is smeared out.

One possible explanation follows. Fluids trapped in permeable crustal rocks above a heat source and beneath a layer of low-permeability sediments and rock (cap rock) can convect. In regions of high heat flow such as the Guaymas basin this convection can be rapid enough to keep the fluids in the zone well mixed. The mixing might efficiently transfer heat over large lateral distances. If this is occurring, we would expect to see (1) conductive heat flow highs above rising convection limbs and lows above descending limbs, (2) these highs and lows oscillating around a fairly constant conductive heat flow mean, and (3) thermal fluids venting wherever breaks occur in the low-permeability cap rock. These properties are indicated in the Guaymas basin, particularly at the central troughs. Away from the central troughs these effects are probably highly damped by the thick sedimentary cover. We have not located any areas outside the central troughs which we believe are sites of active thermal discharge; however, our data coverage is far from complete. One suggested area is the heat flow profile across the midbasin transform fault [*Lawver and Williams,* 1979]. If this heat flow high is due to hydrothermal effects, it is probably a result of fault-related permeability increases. Although the site of this profile may not be a hydrothermal discharge area, the localized heat flow high suggests that the potential for such discharge areas exists along the transform faults.

CONCLUSION

One obvious consequence of applying our hydrothermal model is the resulting release of hot water into the basins. We towed bottom temperature sensors in the Guaymas troughs, biasing our observations toward the edges of the troughs [*Lawver and Williams,* 1979]; however, we concentrated our effort in the northern end of the northern trough. In hindsight we realize this was an unfortunate choice, since this area has far less evidence of present-day hydrothermal venting. We did not see any thermal anomalies. The high He_3 anomaly reported by H. Craig (oral communication, 1978) and the surface sediment metallogenic enrichment (M. Kastner, oral communication, 1978) seem to indicate a need for venting enriched hydrothermal fluids directly into the bottom waters. M. Kastner (oral communication, 1978) found increased manganese concentrations in the deepest parts of the troughs both in the sediments and in the interstitial waters. The concentrations dropped off up the wall of the trough, indicating that the primary vents are along the base of the walls and in the center of the troughs. In addition, dead clams were found around the hydrothermal vent in the northern trough [*Lonsdale,* 1978], which indicates that hydrothermal vents are ephemeral [*Corliss et al.,* 1979] and may be quite common. Drilling in the troughs of the Guaymas basin by the *Glomar Challenger* should produce evidence of a definite increase in hydrothermal alteration at the basement-sediment interface over what is normally found at that interface. Our heat flow data and the above cited data all support the idea that substantial heat loss results from the discharge of thermal waters in the Guaymas basin.

We feel we now have enough information to speculate about the general characteristics of fluid flow in the Guaymas basin hydrothermal system. In this inferred system, water descends into the crust through faults and fractures at the central depressions and mixes with the large volume of pore water. The water is then heated, and while still beneath the central depression, much of it rises through other faults or fractures and is then discharged into the bottom water. The remaining fluids travel outward into older crust, where convective mixing reduces the lateral temperature differences. A limited amount of recharge and venting may also occur in this region. Most of the conductive heat flow variations we see away from the central trough are probably due to variations in thickness of the cap rock and variations in the fluid temperatures within the deep regional hydrothermal system. The thermal waters continue to migrate until they find a pathway to the sea floor. Such pathways may exist locally in the transform faults; there may also be others to the sides of the central troughs.

One last observation which can be drawn from the heat flow data is that the intrusive activity in the Guaymas basin is episodic and that the episodes do not take place simultaneously along the length of a spreading segment. The plate motion could be relatively continuous, but the intrusive pulses are controlled by additional mechanisms, probably related to the time-varying strength of the intruded materials.

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